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Tropopause fold occurrence rates over the Antarctic station Troll (72° S, 2.5° E)

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Abstract. One of the important mechanisms of stratosphere–troposphere exchange, which brings ozone-rich stratospheric air to low altitudes in extratropical regions, is transport related to tropopause folds. The climatology of folds has been studied at high latitudes of the Northern Hemisphere with the help of radars and global models. Global models supply information about fold occurrence rates at high latitudes of the Southern Hemisphere as well, but so far comparisons with direct measurements are rare. The Moveable Atmospheric Radar for Antarctica (MARA), a 54.5 MHz wind-profiler radar, has been operated at the Norwegian year-round station Troll, Antarctica (72° S, 2.5° E) since December 2011. Frequent tropopause fold signatures have been observed. In this study, based on MARA observations, an occurrence rate statistics of tropopause folds from December 2011 until November 2012 has been made, and radar data have been compared with the analysis from the European Center for Medium-Range Weather Forecasting (ECMWF). The fold occurrence rates exhibit an annual cycle with winter maximum and summer minimum and suggest significantly higher occurrence rates for the given location than those obtained previously by global model studies.

Keywords. Meteorology and atmospheric dynamics (Climatology; Mesoscale meteorology; Polar meteorology)

1 Introduction

Tropopause folding is an important mesoscale process and likely one of the major sources of stratosphere–troposphere exchange (STE) in the extratropics (Holton et al., 1995). It has been studied intensively in the mid- and high latitudes by direct observations or high-resolution modelling (see e.g. Van Haver et al., 1996; Beuermann et al., 2002; or Semane et al., 2007). Among direct observation methods, VHF radars in particular have proved to be a very useful tool in the study of tropopause folds. In the Northern Hemisphere, folds at mid-latitudes were studied with the help of Vaughan et al. (1994), Hocking et al. (2007) or at Arctic latitudes by Rao and Kirkwood (2005). Improved knowledge of tropopause folding processes is needed for understanding of the stratospheric source in the long-term development and budgets of tropospheric ozone (O_3). In the case of polar regions, this knowledge may also aid in the explanation of the variation of many trace gases and their isotopic composition in the climate records stored in ice (see e.g. Helsen et al., 2007). Studies estimate the importance of the stratospheric source for tropospheric O_3 in a wide spectrum of values. Based on global European Center for Medium-Range Weather Forecasting (ECMWF) datasets, 40–60 % of pre-industrial tropospheric O_3 is estimated to come from the stratosphere (Lelieveld and Dentener, 2000). An estimate of 23 % is based on a tagged tracer method in a global chemical model (GCM) by Sudo and Akimoto (2007) and down to 0.5 and 2 % for high latitudes in the Arctic (Stohl, 2006) and Antarctic (Stohl and Sodemann, 2010) based on a Lagrangian dispersion model. In addition to these transport studies, a study of surface O_3 variations using a GCM by Tarasova et al. (2007) concluded that up to 55 % of surface O_3 in high latitudes originates in the stratosphere. With these diverse results, better understanding of the climatology and occurrence of STE processes is needed to decrease the uncertainties of the estimates. Studies by Sprenger et al. (2003) and Sprenger and Wernli (2003), based on global meteorological datasets, showed that STE due to tropopause folds at the extratropical tropopause is important especially

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in mid-latitudes, but suggested that these events are rather rare at high latitudes. For the high latitudes of the Northern Hemisphere, these studies suggested fold occurrence rates substantially lower (0–2 %) than the study based on several continuous years of VHF radar measurements by Rao et al. (2008) (5–10 %). The studies also described an annual cycle of tropopause fold occurrence with winter maxima and summer minima, which was confirmed by Rao et al. (2008). This can mean that, although the models are representing the processes leading to formation of tropopause folds, the folds were not resolved with high enough resolution in the models, thus leading to underestimation of fold occurrence rates. For the Southern Hemisphere the study by Sprenger et al. (2003) estimated occurrence rates of tropopause folds in high latitudes to be 0–4 %, with nearly 0 % occurrence rates in summer months (December, January, February) in the areas of Wasa (73° S, 13.5° W) and Troll (72° S, 2.5° E) station, where starting in 2007 a VHF radar – MARA – was located. A case study of a tropopause fold observation at Wasa station by Mihalikova et al. (2012) showed an agreement between ozonesonde observations and radar measurements as well as improved representation of a tropopause fold by high-resolution modelling. Since December 2011, MARA has been located at Troll station, and it operates continuously throughout the year. This gives us the possibility to look at occurrence rates of tropopause folds in this area for the whole year, as observed by radar.

2 Data description

2.1 Radar observations

Observations used in this study were made by MARA (Moveable Atmospheric Radar for Antarctica), which is an interferometric 54.5 MHz wind-profiler radar. MARA was located in the summer season 2006/2007 at Wasa (73° S, 13.5° W) station in Antarctica. It was run during subsequent summer season months until the season 2010/2011. During this time a tropopause fold observation was successfully made and reported (Mihalikova et al., 2012). However, the database was insufficient to infer any information about tropopause fold occurrence rates. Since the summer season 2011/2012, MARA has been located at the Norwegian station Troll (72° S, 2.5° E) and has been in continuous operation since December 2011. This gives us an opportunity to analyse a whole year of tropopause fold observations. MARA measures the profiles of echo power, auto- and cross correlations at and between 3 receivers (connected to separate antenna sub-arrays) and Doppler shift. Signal-to-noise ratio (SNR) is derived from the echo power, and horizontal wind speeds are calculated using the full correlation technique (Holdsworth and Reid, 1995). Also measured, but not used in this study, are the vertical wind speeds determined from the Doppler shift. For easier direct comparison of MARA data with ECMWF data, buoyancy frequency is calculated. These calculations are done based on the fact that, for vertically pointing radars operating around 50 MHz, the echo power returned from the upper troposphere and lower stratosphere, where humidity effects are negligible, is mostly determined by temperature gradients, with allowance for the distance from which the signal is returned, and the scale height of atmospheric density. Estimates of static stability can be thus made based on the echo power:

$$R_{\mathrm{B}}{}^2 = F_e\, z\, \exp(z/H)\, P_{\mathrm{r}}{}^{1/2}. \quad (1)$$

Here P_{r} is radar echo power, z height and H atmospheric scale height (6700 m). F_e is a constant of proportionality and independent of height. This constant can be found by comparison with radiosonde measurements. In our case, a radiosonde measurement was available on 27 January 2012. The constant of proportionality was calculated based on this measurement and applied to the whole time series of radar measurements. F_e is generally found to be independent of time (Kirkwood et al., 2010) provided the radar characteristics (antenna gain and loss, transmitter power) remain the same. In the summer season 2012/2013, five more radiosonde measurements were realized at the radar site. The same constant of proportionality was found based on these measurements with a standard deviation of 8 %. When humidity is or can be assumed to be negligible, as in the upper troposphere and lower stratosphere, R_{B} provides a good estimate of buoyancy frequency (Kirkwood et al., 2010, or for further details Hooper et al., 2004).

During the time frame used in this study, MARA ran in several operating modes. For the analysis here, the following modes were used for the SNR and buoyancy frequency calculations: from December 2011 until mid-January 2012, fcd_300i; mid-January to mid-February 2012, fca_150; and from mid-February until November 2012, fcw_150. These provided good height resolution (200, 150 and 100 m respectively) but relatively low SNR. Therefore throughout this time measurements made by operating modes fcw_300 and fca_4500 with height resolutions of 300 and 600 m but higher SNR were used for analysis of the wind speeds and directions in the upper troposphere and tropopause region. Details of MARA radar and the modes of operation are summarised in Table 2.1.

2.2 ECMWF data

A comparison of profiles observed by MARA with time profiles constructed from ECMWF data for the MARA location was made. For this purpose, the ECMWF operational analysis data for wind components and temperature (used in the calculations of buoyancy frequency) on model levels were used. These data are based upon the T1279L91 spectral model, which is available with a time resolution of 6 h. Around 55 out of the 91 vertical levels cover the region from the ground up to around 16 km. In the analysis process,

Table 1. MARA: technical details and radar operating modes December 2011–November 2012.

Location	72° S, 2.5° E				
Altitude	1275 m a.s.l.				
Frequency	54.5 MHz				
Max. duty cycle	7.5 %				
Peak power	20 kW				
No. of receivers:	3				
Operating modes	fca_150	fcw_150	fcd_300i	fcw_300	fca_4500
Sampling resolution	150 m	100 m	200 m	300 m	600 m
Code	none	none	none	8-bit complementary	8-bit complementary
Further information:	http://www.irf.se/link/MARA_AFP_IRF				
Online data:	http://www.irf.se//program/paf/?link=Data				

tropopause maps (2 pvu level geopotential height and wind speed and direction maps) and maps of potential vorticity on the 300 K and 315 K potential temperature level were also utilised.

3 Methodology and results

As was shown by previous studies (in the Northern Hemisphere Rao and Kirkwood, 2005, and in the Southern Hemisphere Mihalikova et al., 2012), folds can be positively identified in radar data by static-stability features which agree closely with layers of enhanced ozone measured by colocated in situ measurements by ozonesonde. This makes radar observations a powerful source of information about the occurrence rates of tropopause folds in areas without the possibilities of targeted ozonesonde measurement campaigns. In this study the properties of tropopause fold occurrence rates during the winter (June, July, August) and summer (December, January, February) months of the Southern Hemisphere are investigated.

Analogously to the study done by Rao et al. (2008) for a radar site at Arctic latitudes, a fold in the radar data is identified, if the following conditions are met: if the buoyancy frequency or SNR data show a change in the altitude of the tropopause, which can vary from several hundred meters up to 3 km, and there is a sloping high-reflectivity structure visible, descending from the tropopause level into the middle or lower troposphere. The wind velocities in the upper troposphere should also be greater than 30 m s^{-1} (based on WMO definition of the jet stream), and large wind shear should be observed along the frontal zone.

Data were investigated for cases fulfilling these conditions, using a partly automatic, partly manual method. The objective part of the analysis represents the analysis of change of tropopause height, where an algorithm for tropopause height detection was developed. The tropopause was detected based on approximately 3 h running mean of buoyancy frequency data as the height with the steepest gradient of buoyancy frequency over a vertical distance of 600 m between 6 and 12 km height. After that, all cases with a change in tropopause height of 1 km or more, over a 3 h period, were highlighted and these were further investigated for the rest of the conditions subjectively.

Two case studies of tropopause fold observations are presented here in detail to illustrate typical conditions. The folds were identified based on MARA observations, and the synoptic situation is depicted with the help of ECMWF analysis data.

3.1 Case study 1: 21 and 22 June 2012

On 21 and 22 June 2012, a ridge of high pressure was located to the north-west of Troll and a deep low pressure system to the east of Troll station. A jet stream with wind speeds over 45 m s^{-1} was located between these synoptic structures. In the night from 21 to 22 June 2012, a streamer of potential vorticity (visible at the 300 K potential temperature level – not shown here) with an associated tropopause fold on the right flank of the jet stream crossed over the site of the MARA radar. Measurements of this event are shown in Fig. 1. The SNR, buoyancy frequency and horizontal wind direction and wind speed measured by MARA are shown on the left, and a profile constructed from ECMWF analysis data is shown on the right side of the figure. The change of height of the tropopause (black dots in SNR and buoyancy frequency panels) is visible as the fold comes over the site of MARA (21 June late evening) together with a sloping structure descending deep into the troposphere. This event was accompanied by a substantial wind shear detectable along the frontal zone (especially in the wind speed panel). At the same time strong vertical velocities were observed, which indicate the presence of mountain waves (not shown here). According to the aforementioned criteria, these data suggest that a deep tropopause folding event took place at this time. From the comparison with ECMWF-constructed profiles, it can be seen that the ECMWF analysis of wind speed and direction agrees well with the observations. There is also sloping structure, similar to that observed, visible in the ECMWF-calculated buoyancy frequency profile. However, its structure is less detailed because of the lower space and time resolution of the model. The vertical black line in Fig. 1 represents the

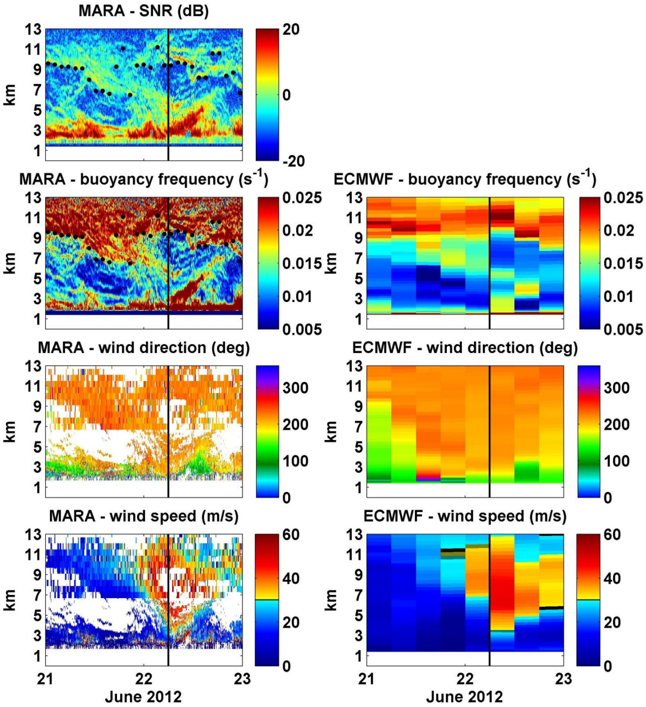

Fig. 1. Observation of a tropopause folding event on 21 and 22 June 2012 at Troll station, Antarctica, by MARA radar (left side) and as seen by ECMWF-constructed time profiles (right side). The indicated height is height above mean sea level. Black dots represent the radar tropopause height. Vertical black line represents the time (22 June 2012, 06:00 UTC) corresponding to the vertical cross section and tropopause map in Fig. 2.

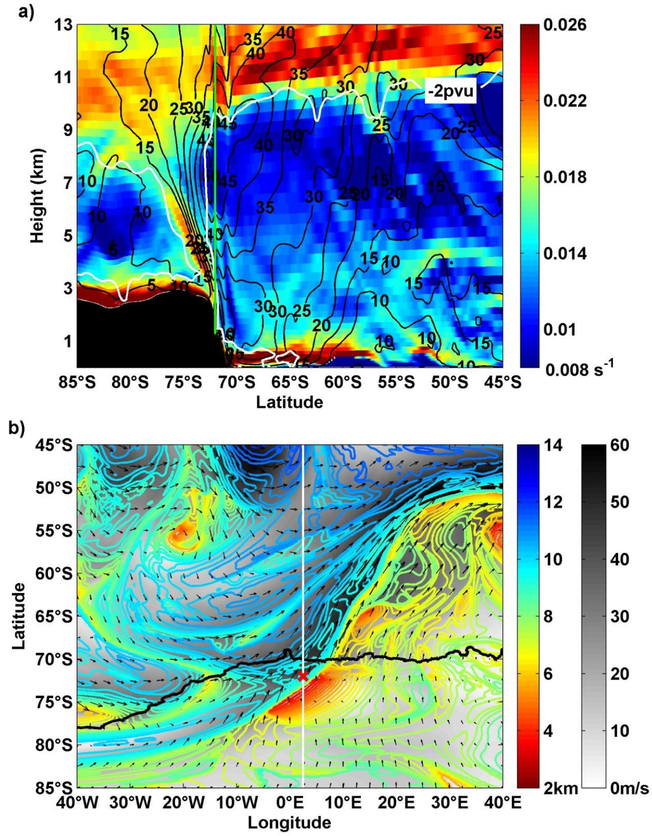

Fig. 2. ECMWF analysis on 22 June 2012, 06:00 UTC. **(a)** Vertical cross section of buoyancy frequency along 2.5° E longitude. White line shows the dynamical tropopause level (−2 pvu), and wind speed contours are indicated in black. Vertical green line represents the position of MARA measurements. **(b)** shows the height, wind speed and direction at the dynamical tropopause level. MARA position is indicated by a red cross, and the vertical white line represents the position of the cross section in **(a)**.

time (22 June 2012, 06:00 UTC) when the cross section and tropopause map in Fig. 2 were plotted. Figure 2a shows the vertical cross section along 2.5° E longitude. A deep folding event is visible in the buoyancy frequency data and the −2 pvu dynamical tropopause (white line) to the south of MARA location (vertical green line). Wind speeds in the upper troposphere reach over 45 m s^{-1}, which is consistent with the radar measurements. The conditions at the dynamical tropopause level are shown in Fig. 2b, in which topography of the tropopause level, wind speed and direction are depicted. The ridge of high pressure and the jet stream located to the north and north-west of the MARA location (red cross) and the fold to the south from MARA are clearly indicated by the height of the tropopause. The vertical white line represents the position of the vertical cross section from panel (a) of the figure. This case represents a typical radar observation of a deep tropopause fold event at Troll station.

3.2 Case study 2: 24 and 25 January 2012

Deep folding events like the one described in Sect. 3.1 are prevalent in the data mainly in the winter months. However, cases of shallow folding are also present and observed in MARA data and are characteristic mainly for summer months. One example of a folding event which was also accompanied by lower wind speeds in the associated jet stream is the fold observed on 24 and 25 January 2012. In this case the fold was associated with a shallow high level cut-off low pressure system over MARA, which was slowly filling in, and a weak high pressure ridge reaching MARA site from the north-east. MARA observations of this event are shown in Fig. 3 together with the ECMWF-constructed time–height profiles. On 24 January a change of the detected tropopause height of around 1 km is visible in the buoyancy frequency data as well as a weak structure sloping down to the mid-troposphere (around 4.5 km height). Wind shear in wind direction and speed is also visible. However, the wind speeds just reach the value of 30 m s^{-1}, which is the threshold chosen for detecting a fold. ECMWF profiles, given their 6 h time resolution, represent the observed change in wind direction and speed in agreement with MARA observations. However, the change of tropopause height in the buoyancy

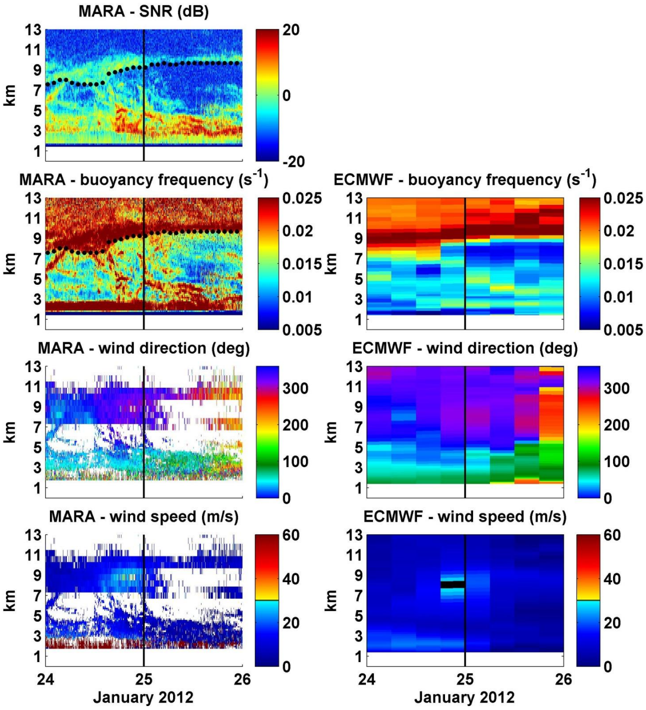

Fig. 3. Observation of a tropopause folding event on 24 and 25 January 2012 at Troll station, Antarctica, by MARA radar (left side) and as seen by ECMWF-constructed time profiles (right side). The indicated height is height above mean sea level. Black dots represent the radar tropopause height. Vertical black line represents the time (25 January 2012, 00:00 UTC) corresponding to the vertical cross section and tropopause map in Fig. 2.

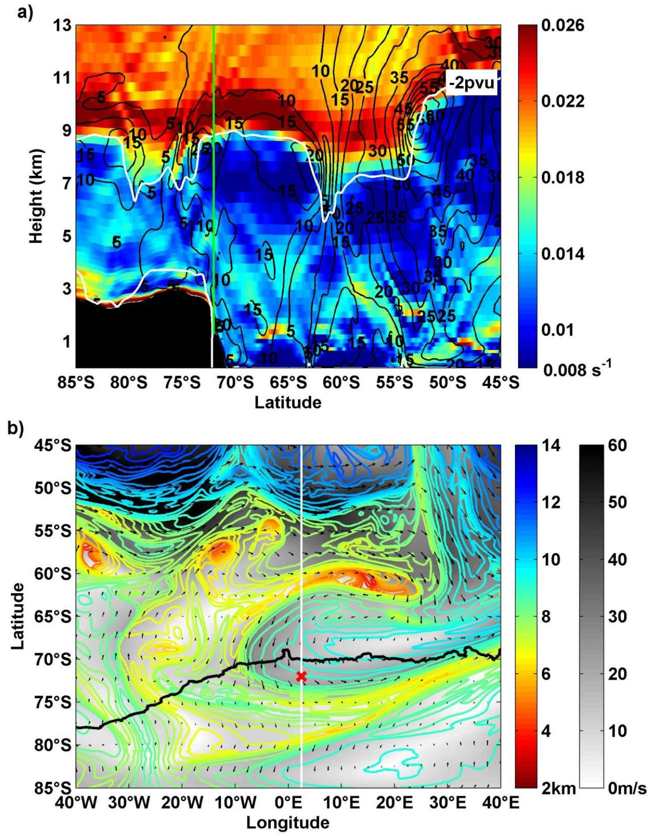

Fig. 4. ECMWF analysis on 25 January 2012 00:00 UTC. **(a)** Vertical cross section of buoyancy frequency along 2.5° E longitude. White line shows the dynamical tropopause level (−2 pvu), and wind speed contours are indicated in black. Vertical green line represents the position of MARA measurements. **(b)** shows the height, wind speed and direction at the dynamical tropopause level. MARA position is indicated a by red cross, and the vertical white line represents the position of the cross section in **(a)**.

frequency data is not as pronounced as in the observed data, although some down-sloping structure is visible in ECMWF profiles as well. Again the vertical black line represents the time (25 January 2012, 00:00 UTC) when the vertical cross section and the tropopause map in Fig.4 were constructed. In panel (a) the observed tropopause fold is located south of the MARA position (green vertical line), and the −2 pvu line reaches only down to around 6.5 km, representing a rather shallow fold-like structure. The tropopause map Fig.4b shows the position of the high pressure ridge to the north of MARA (red cross) and the weak jet stream (just around 30 m s^{-1}) associated with this event. The radar observations suggest that the deepness of the tropopause fold is more than the ECMWF −2 pvu level would suggest. Previously it has been shown by high-resolution modelling that, with improved spatial resolution of a model, the model representation of a radar-observed fold is significantly improved and matches also the observed vertical profile of ozone concentration in detail (Mihalikova et al., 2012). This may have implications for future model-based studies (e.g. ones based on dynamical tropopause properties) and assessments of fold contributions to stratosphere–troposphere exchange in polar latitudes.

3.3 Occurrence rates of tropopause folds

In the two previous subsections, the use of criteria to identify tropopause fold events in MARA data was demonstrated. These criteria were previously used also in the Northern Hemisphere to create a climatological study of tropopause folds at Arctic latitudes (68° N) by Rao et al. (2008). By adopting the same rules, we gain information which is directly comparable with the previous study. During the measurement period from December 2011 until November 2012, 48 folds were identified in the data. Percentage fold occurrence was calculated as 100 times the total number of folds observed divided by the total number of observational days. So this represents an average percentage fold occurrence of 13 %. Percentage fold occurrence rates were calculated for individual months as well and are shown in Fig. 5. Here we can see that the occurrence rates in the winter months (15–26 %, which represents 5 to 8 observed folds per month) are much higher than in the summer months (6–7 % – 1 to 2 observed folds per month). The winter season is characterized by a significantly higher number of observed tropopause folds happening in a shorter time frame compared to the summer season. The folding events are often accompanied by the concurrent observation of mountain lee waves at this particular site, which can increase irreversible mixing of ozone-rich air masses brought to lower altitudes by tropopause folds (Kirkwood et al., 2010) and possibly influence the O_3 gradients even in the lower troposphere (Mihalikova and Kirkwood, 2011).

We have to bear in mind that only one season of measurements from Troll station is available so far, and thus we cannot state if these occurrence rates are around the average, higher or lower for this location. The seasonal change of tropopause fold occurrence with a winter maximum and a summer minimum agrees with the study from Rao et al. (2008), which showed a similar annual cycle in the high latitudes of the Northern Hemisphere. A recent radar study of the tropopause region reports a similar annual cycle of tropopause folds with winter maximum peak but with half the number of observed folds at Davis station (68.5° S, 78° E) on the Antarctic coast. This study uses a different algorithm for tropopause fold detection in radar data based on returned echo power and not buoyancy frequency. It does not take into consideration horizontal winds as these were not available for the site (Alexander et al., 2012). Qualitatively both these studies agree with the ECMWF-model-based 1 yr climatological global study by Sprenger et al. (2003), which also showed an annual cycle for tropopause fold occurrence in both hemispheres, but mainly for mid-latitudes. In the latter study the tropopause fold occurrence was identified from the topology of the dynamical tropopause (2 pvu level) in the ECMWF operational model data. The folds were divided into three categories according to their deepness based on vertical changes in pressure at the dynamical tropopause intersections. In the high latitudes of the Southern Hemisphere, for a rather wide area around Troll station, the fold occurrence frequency was found to be up to 1–4 % for shallow folds, 0.3–1 % for medium folds and 0.1 % for deep folds for either summer or winter season with winter season leaning towards the higher values. Thus the detected total occurrence rate of folds is in significant disagreement with the status observed by the MARA radar. In the area of Davis station, the study by Sprenger et al. (2003) reports total occurrence rates of tropopause folds around 4–9 %, again with higher percentage for winter months. This could suggest that, around Davis station on the coast, the tropopause folds are expected to be observed more frequently than at Troll station, which is located at the edge of the Antarctic plateau. Based on the radar studies, this seems to be not the case. However, in addition to the difference in the working definition of tropopause folds, all of these studies are based on only a limited amount of data with different properties (observations or model data), and do not take into account possible inter-annual differences. Further studies and long-term observations are needed to determine the climatology of tropopause folds in the Antarctic latitudes.

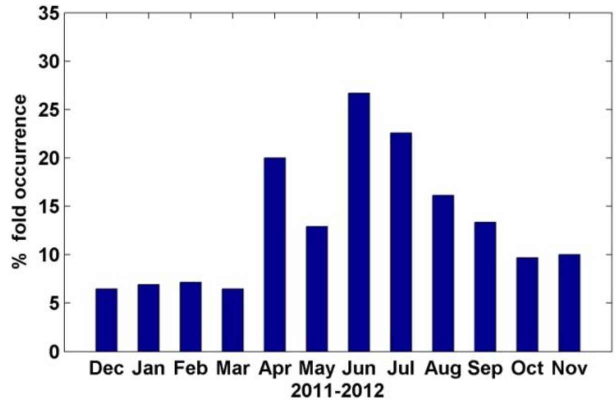

Fig. 5. Percentage fold occurrence at Troll station between December 2011 and November 2012.

4 Summary and conclusions

Information about the occurrence rates of tropopause folds in high latitudes of either the Northern Hemisphere or Southern Hemisphere is still very scarce, but the tropopause fold annual cycle seems to exhibit the same properties in both hemispheres. A winter maximum of observed tropopause folds at Troll station, Antarctica (15–26 % occurrence rate – 5–8 folds per month), is characterized by a higher number of folding events. Summer is characterized mainly by observation of lower number of tropopause folds (6–7 % occurrence rate – 1–2 fold observations per month). The percentage occurrence rates for the winter and summer seasons of 2012 probably partially underestimate the fold occurrence rates. The reason for this is that, during the whole observation period but mainly in the summer season, folding-like events were identified in the data, which were not included in the statistics. The reason was usually the observed wind speeds did not reach 30 m s^{-1} in the upper troposphere, and the change of the tropopause height was less than 1 km or happened over a longer than 3 h time frame. These chosen values for the selection criteria are arbitrary, mainly based on experience and measurement possibilities, and are still open for discussion. Folding-like events, when measured wind speeds over the observation site do not reach decided 30 m s^{-1}, can in reality be tropopause folding events, which bring ozone-rich air mass from the lower stratosphere or extratropical transition layer (see e.g. Gettelman et al., 2011) to significantly lower altitudes, as suggested by radar measurements, ozonesonde observation and high-resolution modelling for a summer-fold at Wasa, Antarctica (Mihalikova et al., 2012).

An earlier ECMWF model-based global study found an occurrence rate of tropopause folds in high latitudes up to

4 % (Sprenger et al., 2003). It was, probably, not always able to detect folding events as their detectability in the dynamic tropopause shape is highly dependant on the model resolution and also on the level chosen to represent the dynamical tropopause. Presently, various values of potential vorticity are used to represent tropopause height. Recent studies show that, for polar regions, the value of 2 pvu is suitable to represent the dynamical tropopause. These studies are either based on ECMWF model data (e.g. Kunz et al., 2011) or comparison of model with radar measurements (e.g. Alexander et al., 2012). Comparison studies show that the relationships between radar tropopause height, ozone tropopause height and 2 pvu level are in good agreement under most synoptic conditions as both of these tropopauses are dynamically controlled. However, they might diverge from the tropopause height defined by temperature gradient (Alexander et al., 2012). Because models can be useful tools for global studies, high-resolution models might need to be employed to resolve the dynamical tropopause in better detail in order to represent a dynamical tropopause in folding events which is closer to reality. Further studies are needed to determine the climatology of tropopause folds in high latitudes, which is important for proper evaluation of stratosphere–troposphere exchange and tropospheric ozone budgets in these remote areas.

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